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Final Technical Report

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Fundamental Studies in Dynamic Plasticity

to

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Research Objectives

The principal objective of the research on this project has been to develop improved understanding of the plastic response of metals at strain rates of 10^5 s^{-1} and higher. This objective has been pursued primarily by the development of a strain-rate change test for probing the plastic response of a metal being sheared at strain rates of 10^5 s^{-1} to 10^6 s^{-1} in a pressure-shear plate impact experiment. Such a test makes it possible to distinguish between the rate sensitivity of the flow stress at fixed dislocation structure, and the rate sensitivity of strain hardening. These effects cannot be distinguished in the usual tests at constant strain rates.

A second objective arises from the main result of the research on the principal objective; namely, that the rate sensitivity at high strain rates is associated primarily with the rate sensitivity of strain hardening. Consequently, improved understanding of strain hardening takes on greater importance and has been addressed as a second objective. Quasi-static compression tests have been conducted on aluminum single crystals to clarify the interaction between slip on one slip system and hardening on another. Such clarification is required to allow the development of reliable models for plastic flow based on slip on multiple slip systems. To further understand the details of plastic flow, especially in regions of large strain gradients, a Moire microscope has been developed in a collaborative effort between T. W. Shield, supported as a post-doc on this project, and Professor K.-S. Kim.

Principal Results

A series of experiments on OFHC copper was conducted and a constitutive model was developed which allows the principal results of the experiments to be simulated accurately. Simulations of the strain-rate-change tests showed that in these experiments the rate sensitivity of the flow stress at fixed structure is significantly weaker than the rate sensitivity of strainhardening. This result is viewed as being of fundamental importance in the development of constitutive equations for modeling plastic flow as well as for advancing the micro-mechanical understanding of plastic flow at high strain rates. Results of this research are presented in a Ph.D. thesis by Wei Tong.

In the strain-rate-change experiments, the specimen is strained at shear rates up to 10^6 s^{-1} for one microsecond and then strained at substantially lower shear

rates for another microsecond. The specimen is sandwiched between two hard elastic plates in a pressure-shear plate impact configuration to impose conditions of simple shear at very high strain rates and constant hydrostatic pressure. Marked increases in flow stresses are observed at strain rates of 10^5 s^{-1} and higher. Flow stresses decrease gradually when the strain rate drops sharply in all strain-rate-change tests. Theoretical analyses of the nonlinear wave propagation within the specimen are carried out using a general internal variable formulation in which the hardening rate depends on the rate of deformation. The governing system of hyperbolic partial differential equations is solved using a finite-difference scheme; the computational results are compared with the experimental results. Only the internal variable model which incorporates a strong rate sensitivity of strain hardening is successful in describing the observed response to the change in strain rate. The generation and evolution of dislocation cells appears to be the dominant micromechanical process during the high rate deformation of pure metals.

Both small deformation and finite deformation formulations have been considered. The results of these two formulations are essentially identical, even though the shear strains are as large as 3.0. This insensitivity of the results to finite deformations has been established both by finite element calculations done by Y.J. Lee and by finite difference calculations done by Wei Tong. We have shown that finite deformation effects in simple shear tend to be small as long as the shear stress is small compared to the elastic shear modulus.

Specimens recovered from the plate impact experiments have been examined by J. D. Jarrell using transmission electron microscopy (TEM). Homogeneous equiaxial dislocation cells are found to be the dominant substructure in the deformed specimens. At very large strains some regions show the formation of linear features in which rows of cells are similarly rotated. This formation of intra-granular linear structures is being examined further as a possible predecessor to the formation of shear bands. The evolution of the dislocation cell structure is regarded to be the principal micromechanical hardening process. Saturation of the flow stress is thought to correspond to the formation of essentially a steady state cell structure. Results of this TEM investigation are presented in a Sc.M. thesis by J. D. Jarrell.

Other progress on the understanding of plastic flow has involved studies at low strain rates. Such studies appear to have much to offer for improved understanding

of plastic flow, even at high strain rates in view of the relative importance of strain hardening that was found in the dynamic strain-rate-change tests. One experimental investigation of plastic flow at low strain rates is motivated, in part, by John Basani's recent re-examination of latent hardening. He has argued that the Jackson and Basinski experiments, which are generally interpreted as showing that latent hardening (i.e. hardening of an inactive slip system due to slip on the primary slip system) is greater than the hardening of the primary slip system, have been interpreted incorrectly. He contends that hardening occurs largely, even entirely, on active slip systems but that the rate of hardening on these slip systems depends on the accumulated plastic strain on the other slip systems. This view appears to have merit and, if correct, it has major implications on the form of constitutive relations for plastic flow. We are re-examining the hardening rates on different systems by conducting experiments, analogous to those of Jackson and Basinski, on aluminum single cyrstals. One new feature of our experiments is precision lapping (based on the capability we have developed for plate impact experiments) to ensure that the loaded faces of the specimen are parallel, and perpendicular to the axis of the specimen, so that bending effects are minimized. Another new feature of our experiments is the use of the Moire microscope of Kim and Shield to measure four components of the strain tensor. This detailed recording of the strain makes it possible to be more quantitative about the contributions of each of the most active slip systems than was the case in earlier experiments in which the orientation of slip traces was used to indicate which slip systems were active. These experiments have been conducted by Hai Mei, who is expected to complete his Ph.D. thesis within a few months.

One of the quasi-static studies addresses plastic flow at a crack tip in a single crystal. In this study, Tom Shield, supported by ONR as a post-doc, and Professor K-S. Kim used a Moire microscope, developed by them, to examine the plastic strain field near the tip of a crack in an iron-silicon single crystal. This study was motivated by a recent theoretical analysis by Jim Rice and co-workers that predicted strain fields which appear not to be in agreement with the available, rather limited, experimental results. The experiments by Shield and Kim have enabled them to fully characterize the plastic deformation in the vicinity of the crack. They have been able to show that the fields are not those anticipated by Rice and co-workers,

but are consistent with computer simulations by Mohan and Ortiz.

Experimental results for the plastic deformation field near a crack tip in an Iron Silicon single crystal are given for a crack on the (011) plane with its tip along the $[01\bar{1}]$ direction. The deformation field was analyzed with Moire microscopy on the side surface of the specimen. Complete sets of Almansi strain have been obtained by a digital processing of the Moire fringes. A well-structured asymptotic field has been found in the distance 350 - 500 mm away from the crack tip, where the maximum plastic strain was about 9%. The asymptotic field is composed of seventeen angular sectors. It is observed that in a set of six (i.e. three symmetric) separate sectors the strains are approximately constant in each sector. In another set of six (i.e. symmetric, three connected) sectors, strain is approximately $1/r$ singular. The other five sectors are interconnecting transition sectors. The state of the yield locus and the active slip systems in each sector can be identified by means of the normality rule which requires the plastic strain rates to be normal to the yield surface. The direction of the strain rate is estimated by plotting the in-plane deviatoric strain components for points along circular arcs around the crack tip. The slip systems identified in the strain analysis are compared with the direct observations of the slip texture and the dislocation etch pits. Excellent agreement is found. From the experimental observations it is evident that some of the vertex sectors are composed of two distinct subsectors. One is the subsector of concurrent multiple slip, while the other is the subsector of patchy slip. The patchy slip sector is believed to be formed by plastic instability due to crystal rotation. Unexpected, counter-intuitive unloading sectors are found ahead of the crack tip. These are the sectors observed as the constant strain sectors. Because of these unloading sectors, the crack tip stress and deformation state is substantially different from the HRR type field (Saeedvafa and Rice, 1989) for which proportional loading is assumed. Such strongly non-proportional loading is due to both elastic and plastic anisotropy. The non-proportional loading observed in this experiment shows strong crack-tip shielding which provides a toughening mechanism. Such a toughening mechanism is called anisotropy toughening. The mechanism is characterized by the biaxiality constant of the singular field. In new results to be presented by Kim and Shield at an IUTAM Symposium, the Moire microscope has been extended to include the measurement of out-of-plane deformations.

Publications and Manuscripts

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